NOTES AND CORRESPONDENCE

An Improvement in Forecasting Rapid Intensification of Typhoon Sinlaku (2008) Using Clear-Sky Full Spatial Resolution Advanced IR Soundings

HUI LIU

National Center for Atmospheric Research, Boulder, Colorado*

JUN LI

Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin—Madison, Madison, Wisconsin

(Manuscript received 18 August 2009, in final form 16 November 2009)

ABSTRACT

Hyperspectral infrared (IR) sounders, such as the Atmospheric Infrared Sounder (AIRS) and the Infrared Atmospheric Sounding Interferometer (IASI), provide unprecedented global atmospheric temperature and moisture soundings with high vertical resolution and accuracy. In this paper, the authors investigate whether advanced IR soundings of water vapor and temperature observations can improve the analysis of a tropical cyclone vortex and the forecast of rapid intensification of a tropical cyclone. Both the IR water vapor and temperature soundings significantly improve the typhoon vortex in the analysis and the forecast of the rapid intensification of Typhoon Sinlaku (2008). The typhoon track forecast is also substantially improved when the full spatial resolution AIRS soundings are assimilated. This study demonstrates the potential important application of high spatial and hyperspectral IR soundings in forecasting tropical cyclones.

1. Introduction

Forecasting rapid intensification [e.g., a decrease of 42 hPa in minimum sea level pressure (SLP) in less than 24 h; National Hurricane Center 2006] of tropical cyclones remains a critical challenge. In general, tropical cyclone development requires a favorable environment of moist air, thermo instability, low vertical wind shear, preexisting low-level perturbation, high sea surface temperature (SST), and high ocean heat content (OHC) in the vicinity of tropical cyclones (e.g., Gray 1968; Mcbride and Zehr 1981). However, it has not been demonstrated whether the environmental water vapor and temperature observations will significantly improve the rapid development of tropical cyclones.

Advanced infrared (IR) sounder data from instruments such as the Atmospheric Infrared Sounder (AIRS; Chahine et al. 2006) and the Infrared Atmospheric Sounding Interferometer (IASI; Siméoni et al. 1997) have provided unprecedented environmental temperature and moisture profiles with high vertical resolution and accuracy with good spatial resolution (12–14 km at nadir) in the vicinity of tropical cyclones. The Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin—Madison has developed a method to derive temperature and moisture profiles from advanced IR radiance measurements alone in clear skies and some cloudy-sky conditions on a single field-of-view (SFOV) basis (Li and Huang 1999; Li et al. 2000, 2004; Zhou et al. 2007; Weisz et al. 2007). This research product using the CIMSS hyperspectral IR sounder retrieval (CHISR) algorithm provides AIRS soundings with higher spatial resolution (approximately 13.5 km) than the operational AIRS sounding product (Susskind et al. 2003), with a spatial resolution of 50 km at nadir.

The CIMSS advanced IR soundings are available in clear sky and thin cloud conditions around tropical cyclones and are useful for initializing the environmental

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: Hui Liu, National Center for Atmospheric Research, Boulder, CO 80307.
E-mail: hliu@ucar.edu

DOI: 10.1175/2009JAMC2374.1

water vapor and temperature for forecasting tropical cyclones. A recent study shows that the CIMSS IR water vapor and temperature soundings significantly reduced the forecast track and intensity errors of Hurricane Ike (2008) in its mature stage (Li and Liu 2009). In this study, we will investigate whether CIMSS IR water vapor or temperature soundings in the environment of tropical cyclones are able to improve the definition of the initial vortex and forecast of the rapid intensification of tropical cyclones. We have applied the full spatial resolution temperature and moisture soundings retrieved from AIRS radiance measurements using the CHISR algorithm to the forecast of the rapid intensification of Typhoon Sinlaku (2008) with the National Center for Atmospheric Research (NCAR) Weather Research and Forecasting/ Data Assimilation Research Testbed (WRF/DART) ensemble assimilation system (Anderson 2003, 2007; available online at http://www.image.ucar.edu/DAReS/). The effect of the advanced IR sounding observations on the analysis of the typhoon vortex structure and forecast of the following rapid intensification of the typhoon are examined. We also examined the effect of the full spatial resolution water vapor and temperature soundings separately. It is found that both full spatial resolution advanced IR water vapor and temperature soundings significantly improve the forecast of the rapid intensification and track of Typhoon Sinlaku.

2. Typhoon Sinlaku

On 7 September 2008, a tropical disturbance formed to the northeast of Manila in the Philippines. During the following day, the depression intensified into a tropical storm. At 1200 UTC 9 September 2008, Sinlaku reached an intensity of 975 hPa and became a category 1 typhoon. During the next 24 h, Sinlaku rapidly intensified by approximately 40–935 hPa by 1200 UTC 10 September 2008. It stayed at this intensity until the next day, when it started to weaken. In this study, we will focus on the effect of the AIRS environmental full spatial resolution sounding observations on the 24-h forecast starting at 1200 UTC 9 September 2009.

3. Full spatial resolution hyperspectral IR soundings for Typhoon Sinlaku

The CHISR algorithm has been developed to retrieve atmospheric temperature and moisture profiles from the advanced IR sounder radiance measurements alone in clear skies and some cloudy-sky conditions on a SFOV basis (Li and Huang 1999; Li et al. 2000; Zhou et al. 2007; Weisz et al. 2007). Radiance measurements from all IR channels are used in the sounding retrieval process. This CIMSS research product provides AIRS soundings with a higher spatial resolution of approximately 13.5 km than the operational AIRS sounding product, which is based on the Advanced Microwave Sounding Unit (AMSU)/AIRS cloud-clearing algorithm (Susskind et al. 2003). The clear-sky IR soundings provide good information about the water vapor and temperature environment of tropical cyclones.

The AIRS IR soundings are available during 0300–0700 and 1600–1900 UTC of each day during the storm's period. Figure 1 shows the locations of the IR moisture soundings used in the assimilation under clear-sky conditions from 0000 UTC 6 September to 1200 UTC 9 September 2008. It can be seen that during 6 and 7 September 2008, there were quite a few soundings in the vicinity of the storm, which may have more direct influence on the analyses of the storm. Most of the IR soundings were located away from the typhoon, which provide valuable observations of the environment of the storm. With an advanced IR sounder in geostationary orbit, more clear-sky soundings can be obtained through frequent observations (Schmit et al. 2009). In the next section, we will see that these IR soundings in the environment of the typhoon do have significant positive influence on forecasting the rapid intensification of the typhoon.

It is noted that starting from 0000 UTC 10 September 2008, this typhoon was well sampled during the Office of Naval Research (ONR)-sponsored Tropical Cyclone Structure (TCS-08) field program including several penetrations by the air force hurricane hunters (WC-130J). The environment of the typhoon was also well sampled by the Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) dropsondes observations. These valuable observations can be used for further evaluation of the analyses and forecasts of this study.

4. Assimilation experimental design

The WRF/DART ensemble data assimilation system is used to assimilate the full spatial resolution IR sounding observations [for details about DART, see Anderson (2003, 2007)]. One of the challenges for assimilating the IR water vapor observations for mesoscale and convective-scale forecasts, such as tropical cyclones and heavy rainfall, is that the forecast error covariances between water vapor and other model variables are not known. Consequently, it is difficult to use the water vapor observations to make consistent corrections to the errors in the other model variables. DART employs a set (ensemble) of model short-range forecasts to estimate the forecast error covariances. These ensemble-based covariances can lead to better analyses of water vapor and temperature in the assimilation of water vapor–related measurements (Liu et al. 2007).

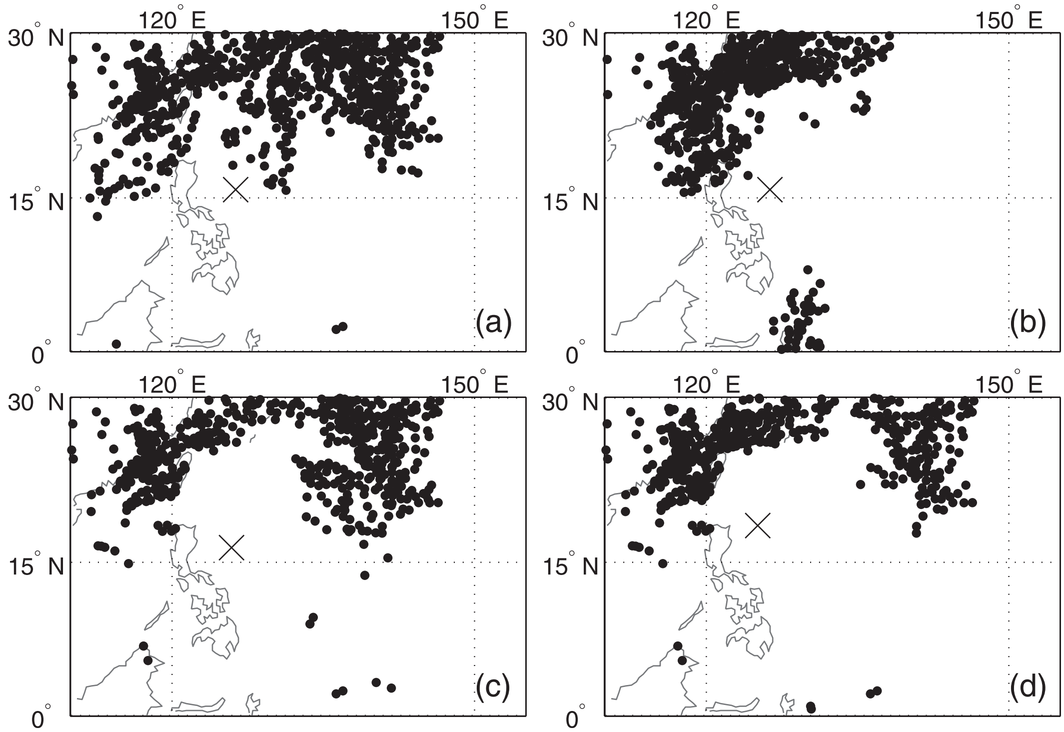

FIG. 1. The spatial distributions of clear-sky full spatial resolution AIRS water vapor mixing ratio soundings during the period of (a) 0000 UTC 6–7, (b) 0000 UTC 7–8, (c) 0000 UTC 8–9, and (d) 0000–1200 UTC 9 Sep 2008.

In the experiments, a 3.5-day assimilation is run first, starting at 0000 UTC 6 September 2008 and cycling the assimilation every 2 h until 1200 UTC 9 September 2008. The initial and boundary ensemble mean conditions are obtained from the 1° × 1° global aviation (AVN) analysis produced by the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction (NCEP). The initial and boundary ensembles are generated by adding random draws from a distribution with the forecast error covariance statistics of the WRF three-dimensional variational data assimilation (3DVAR) data assimilation system to the mean fields. The WRF model for the assimilation is configured with a 45-km horizontal resolution with 45 vertical levels from the surface to the model top at 30 hPa. Thirty-two ensemble members are used in the assimilation experiments.

At the end of the assimilation period, a set of 36-h ensemble forecasts (16 members) initialized from the ensemble analyses on 1200 UTC 9 September 2008 are performed. The forecasts have a 15-km nest grid to better capture the rapid development of the typhoon. It is noted that higher-resolution nests (approximately a few kilometers) would be desirable for forecasting the rapid intensification of tropical cyclones, which will be addressed in future studies.

The control (CTL) run assimilates most conventional observations, including radiosonde, satellite visible and imager water vapor cloud winds, aircraft data, land and ocean surface station and buoy observations, Quick Scatterometer (QuikScat) surface winds, and hurricane position data. The microwave soundings from polar satellites might provide similar information (as seen in Li and Liu 2009), but they are not assimilated in the control run because we would like to fully explore the potential of the AIRS data in this study. In later studies, the microwave sounding data will be added to the control run. The CIMSS-Q, CIMSS-T, and CIMSS-QT runs add the AIRS full spatial resolution moisture, temperature, and both of the moisture and temperature profiles (13.5 km at nadir), respectively.

5. Results

First, we examine the effect of the full spatial resolution IR soundings on the definition of the typhoon vortex structure in the lower and middle troposphere after 3.5 days of continuous assimilation. It is noted that the analyses include the direct effect of the observations at this time and the model's advance of the effect of all the previous observations. Therefore, the analyses' differences between the control run and CIMSS runs involve the WRF model's effect.

The left panel in Fig. 2 shows the Typhoon Sinlaku sea level pressure analysis (ensemble mean of the 32 ensemble

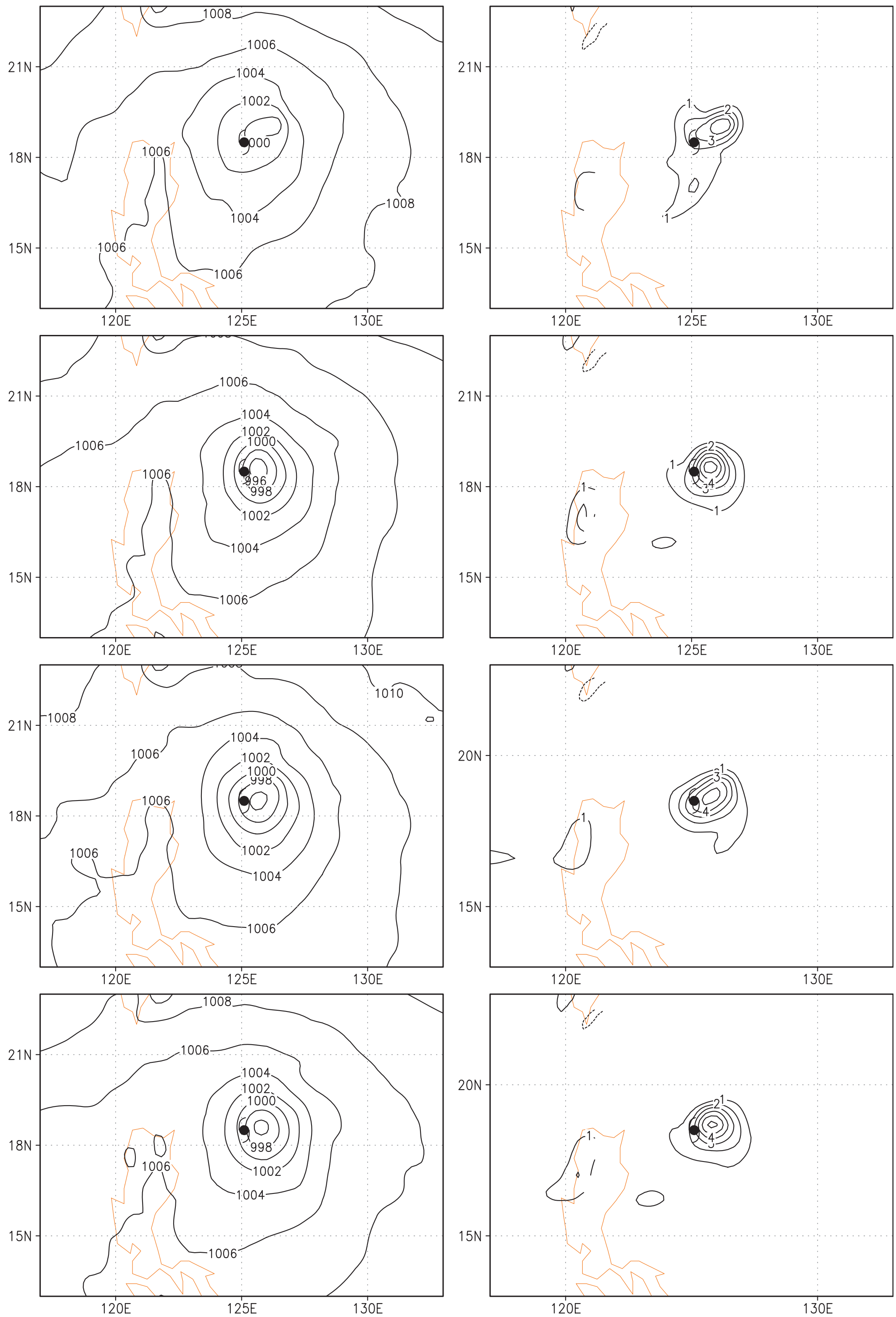

FIG. 2. (left) Minimum SLP (hPa; mean of the 32 ensemble members) and (right) relative vorticity analysis (1.0^{-4} s^{-1}) at 850 hPa of Typhoon Sinlaku at 1200 UTC 9 Sep 2008 for (top) the control run, and the assimilating full spatial resolution AIRS (second row) CIMSS-Q run, (third row) CIMSS-T run, and (bottom) CIMSS-QT run.

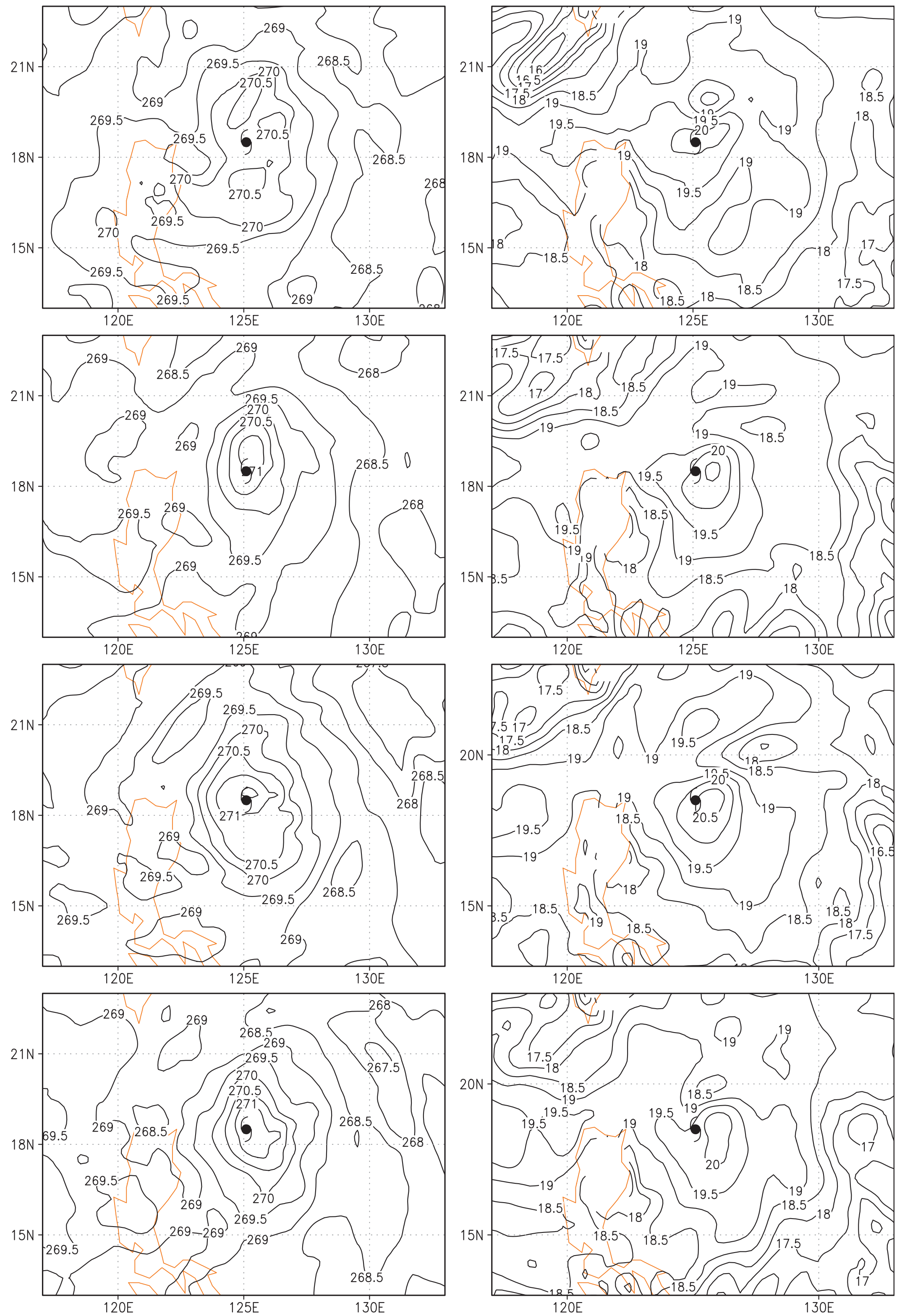

FIG. 3. As in Fig. 2, but for (left) temperature (K) at 500 hPa and (right) water vapor (g kg^{-1}) at 950 hPa.

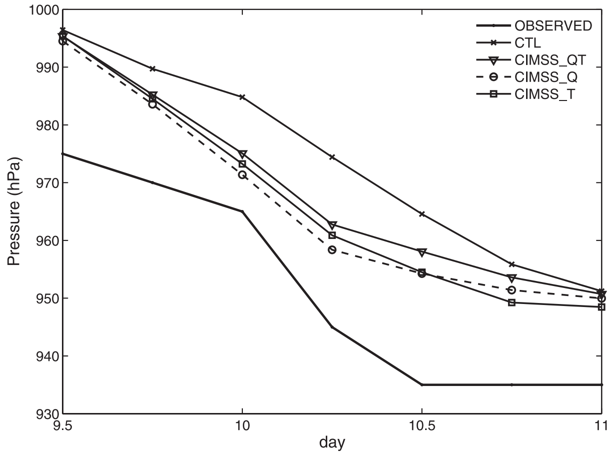

FIG. 4. The 36-h forecasts of minimum SLP (mean of 16 ensemble members) at the 15-km nest grid for Typhoon Sinlaku, which are initialized from the analyses at 1200 UTC 9 Sep 2008. The thick solid line without symbols represents the observation, and lines with times signs, circles, squares, and triangles are the CTL, CIMSS-Q, CIMSS-T, and CIMSS-QT runs, respectively.

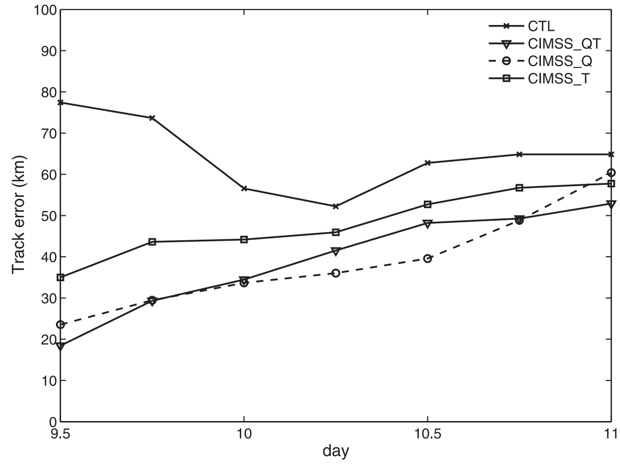

FIG. 5. As in Fig. 4, but for track errors of Typhoon Sinlaku.

members) from the control run, the assimilation of the AIRS full spatial resolution CIMSS-Q run, CIMSS-T run, and CIMSS-QT run. It can be seen that the minimum SLP of the analyses with assimilation of AIRS full spatial resolution moisture and temperature soundings reached 996 hPa at 1200 UTC 9 September 2008; the minimum SLP in the control run is a bit higher, ~1000 hPa. The SLPs of the vortices also have better axis-symmetric distribution when the AIRS full spatial resolution sounding data are assimilated, while the vortex is a bit distorted in the control run. Relative to the observed 975 hPa of SLP at this time, however, the SLP intensities of the analyses are still much weaker, which may be partly due to the coarse resolution of the analysis grid.

The right panel in Fig. 2 shows the relative vorticity analysis (ensemble mean) at 950 hPa from the control run, the CIMSS-Q run, the CIMSS-T run, and the CIMSS-QT run at 1200 UTC 9 September 2008. It can be seen that the control run has a cyclonic vorticity of $\sim 4.0 \times 10^{-4}\ \mathrm{s}^{-1}$. When the full spatial resolution AIRS moisture and temperature soundings are assimilated, the cyclonic vorticity increases to $\sim 6.0 \times 10^{-4}\ \mathrm{s}^{-1}$ and $\sim 5.0 \times 10^{-4}\ \mathrm{s}^{-1}$, respectively.

A warm core of ~271 K at 500 hPa is also well defined near the observed typhoon center when the moisture or/and temperature soundings are assimilated (Fig. 3). In contrast, the warm core is less organized and weaker in the control analysis, where three separated warm areas are collocated (top panel of Fig. 3). In addition, with assimilation of the full spatial resolution AIRS moisture and temperature soundings, the region of the typhoon center is also slightly moister than the control run.

All of the earlier-mentioned results suggest that with the assimilation of full spatial resolution AIRS moisture or/and temperature soundings, the vortex of the typhoon is better defined. This improvement should lead to better forecasts of the typhoon, as seen next.

Figure 4 shows the ensemble mean SLPs of the 36-h ensemble forecasts for the control and CIMSS runs on the 15-km nest grid. The SLP of the forecast from the control run decreases ~31 hPa after 24 h and reached 965 hPa at 1200 UTC 10 September 2008. With the full spatial resolution AIRS temperature or/and moisture sounding retrievals, the forecast of the rapid intensification is much better. The SLP forecast from the CIMSS runs decreases ~40 and ~36 hPa in 24 h, reaching 954 and 958 hPa, which is much closer to the observation.

It is also noted that with the assimilation of the full spatial resolution AIRS moisture and temperature soundings, the forecast track errors are also significantly reduced when compared with the control run (Figs. 5 and 6). The moisture soundings reduce track error more than the temperature soundings.

These results also suggest that the advanced IR moisture observations can have significant influence on the forecasting of tropical cyclones, at least up to 36 h.

6. Summary

This study showed that assimilation of the environmental advanced IR sounding observations can significantly improve the definition of the initial vortex structure in the analysis and forecasting rapid intensification of Typhoon Sinlaku (2008). Both full spatial resolution AIRS moisture and temperature soundings show a positive effect on forecasting the rapid development of the typhoon using the WRF/DART system. More hurricane

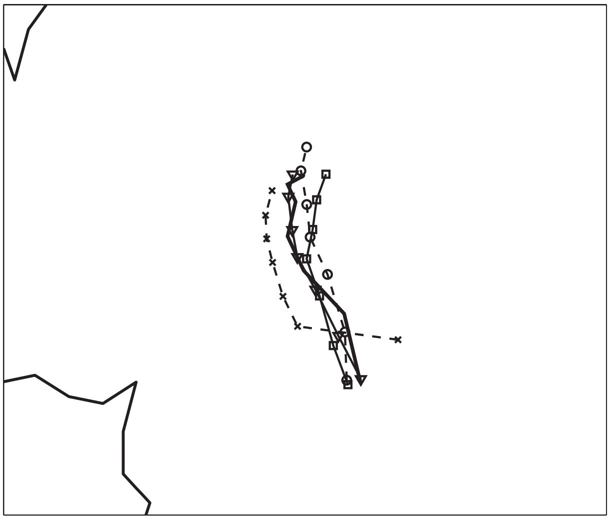

FIG. 6. As in Fig. 4, but for tracks of Typhoon Sinlaku.

cases will be studied using data from advanced IR sounders, such as AIRS and IASI, as well as microwave sounding data, such as AMSU-A and AMSU-B. Experiments will also be extended to include cloudy soundings retrieved from IR radiance measurements.

Acknowledgments. The authors thank Dr. Jinlong Li at CIMSS for processing AIRS SFOV sounding data; Timothy J. Schmit of STAR/NESDIS provided very constructive suggestions on conducting this research. The authors thank Jeff Anderson and Chris Snyder at NCAR for their support of this work. This study is partly supported by NOAA Grant NA06NES4400002.

REFERENCES

Anderson, J., 2003: A local least squares framework for ensemble filtering. *Mon. Wea. Rev.,* **131,** 634–642.

——, 2007: An adaptive covariance inflation error correction algorithm for ensemble filters. *Tellus,* **59A,** 210–224.

Chahine, M. T., and Coauthors, 2006: AIRS: Improving weather forecasting and providing new data on greenhouse gases. *Bull. Amer. Meteor. Soc.,* **87,** 911–926.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.,* **96,** 1649–1668.

Li, J., and H.-L. Huang, 1999: Retrieval of atmospheric profiles from satellite sounder measurements by use of the discrepancy principle. *Appl. Opt.,* **38,** 916–923.

——, and H. Liu, 2009: Improved hurricane track and intensity forecast using single field-of-view advanced IR sounding measurements. *Geophys. Res. Lett.,* **36,** L11813, doi:10.1029/2009GL038285.

——, W. Wolf, W. P. Menzel, W. Zhang, H.-L. Huang, and T. H. Achtor, 2000: Global soundings of the atmosphere from ATOVS measurements: The algorithm and validation. *J. Appl. Meteor.,* **39,** 1248–1268.

——, W. P. Menzel, F. Sun, T. J. Schmit, and J. Gurka, 2004: AIRS subpixel cloud characterization using MODIS cloud products. *J. Appl. Meteor.,* **43,** 1083–1094.

Liu, H., J. Anderson, Y.-H. Kuo, and K. Raeder, 2007: Importance of forecast error multivariate correlations in idealized assimilation of GPS radio occultation data with the ensemble adjustment filter. *Mon. Wea. Rev.,* **135,** 173–185.

Mcbride, J. L., and R. M. Zehr, 1981: Observational analysis of tropical cyclone formation. Part II: Comparison of non-developing versus developing systems. *J. Atmos. Sci.,* **38,** 1132–1151.

National Hurricane Center, 2006: Glossary of NHC terms. [Available online at http://www.nhc.noaa.gov/aboutgloss.shtml.]

Schmit, T. J., J. Li, S. A. Ackerman, and J. J. Gurka, 2009: High spectral and temporal resolution infrared measurements from geostationary orbit. *J. Atmos. Oceanic Technol.,* **26,** 2273–2292.

Siméoni, D., C. Singer, and G. Chalon, 1997: Infrared atmospheric sounding interferometer. *Acta Astronaut.,* **40,** 113–118.

Susskind, J., C. D. Barnet, and J. M. Blaisdell, 2003: Retrieval of atmospheric and surface parameters from AIRS/AMSU/HSB data in the presence of clouds. *IEEE Trans. Geosci. Remote Sens.,* **41,** 390–409.

Weisz, E., J. Li, J. Li, D. K. Zhou, H.-L. Huang, M. D. Goldberg, and P. Yang, 2007: Cloudy sounding and cloud-top height retrieval from AIRS alone single field-of-view radiance measurements. *Geophys. Res. Lett.,* **34,** L12802, doi:10.1029/2007GL030219.

Zhou, D. K., W. L. Smith, X. Liu, A. M. Larar, S. A. Mango, and H.-L. Huang, 2007: Physically retrieving cloud and thermodynamic parameters from ultraspectral IR measurements. *J. Atmos. Sci.,* **64,** 969–982.